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13. ABSTRACT (Maximum 200 words) The general goal of our research is the generation, manipulation, and characterization of coherent and nonclassical matter-wave sources. The research has both a theoretical and an experimental component. Theoretical achievements include the use of nonlinear atom optical techniques to generate beams of entangled atoms and squeezed atomic beams from Bose-Einstein condensates, as well as the generation of entangled atom-photon pairs, the extension of the ideas bosonic atom optics to the nonlinear atom optics to fermionic atoms and to boson-fermion mixtures. We have also started to analyze how the combination of these developments can be applied to the realization and manipulation of molecular fields of tailored quantum statistics On the experimental side we have worked with Cs atoms in optical lattices to implement qubits, quantum gates and circuits. We have demonstrated trapping in deep 3D lattices, initialization by sideband cooling, and single-qubit control. In a second project we have used optical probes to implement continuous weak measurements of collective observables in an atomic ensemble. We have developed a detailed understanding of Faraday measurements of atomic spins, and a novel scheme to probe the pseudospin associated with the atomic clock transition.				
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4. Statement of the Problem Studied

The general goal of our research has been the generation, manipulation and characterization of coherent and nonclassical matter-wave sources, including in particular atom lasers and sources of spin-squeezed and entangled atoms. The research involved both an experimental and a theoretical component.

5-1. Summary of Important Results, Theory Component (Pierre Meystre, PI)

Early theoretical achievements included the use of nonlinear atom optical techniques to generate beams of entangled atoms and squeezed atomic beams from Bose-Einstein condensates, as well as the generation of entangled atom-photon pairs. Early on we have also initiated a study of the magnetic properties of condensates on optical lattices. This work might find applications in quantum information processing and “spintronics.”

This work was soon followed by a slight redirection of our program and by the extension of the ideas of nonlinear atom optics to fermionic atoms and to boson-fermion mixtures. These systems have no analog in traditional optics. They may lead to new physics, for example phonon-induced fermionic BCS coupling, to the generation of nonclassical matter waves based on Pauli blocking, and to possible “fermionic atom lasers.” As a result of the Pauli Exclusion Principle, fermionic atomic beams are intrinsically multimode systems that cannot normally be described by straightforward extensions of the tools of quantum optics. Nonetheless, we have made good progress toward their understanding. For example, we have demonstrated theoretically that matter-wave interferometers based on fermionic atomic beams can be superior to their bosonic

counterparts in the measurement of small phase changes, a situation reminiscent of white-light interferometry in conventional optics.

With the ultimate goal of assessing the practicality of fermionic atom optics, we have developed a multimode input-output formalism that is essential in describing the coupling of fermionic beams in and out of atomic traps, and developed a complete dynamical theory of fermionic four-wave mixing, identifying limiting factors such as “inhomogeneous” broadening resulting from the Pauli Exclusion Principle. We have also considered ways to use Bose-Einstein condensates as nonlinear media to manipulate the properties and the propagation of fermionic beams. Bose-Fermi mixtures have been studied, with the ultimate goal of coherent control of fermions by bosons and the generation of a “fermionic atom laser”. We have also shown that the “phase conjugation” or more precisely time-reversal, of fermionic beams is possible, a phenomenon analogous to Andreev reflection in traditional low-temperature physics where it has proven to be a useful diagnostic tool to investigate the nature of the coupling in high-temperature superconductivity. In future work we plan to determine whether similar applications on fermionic phase conjugations can be developed in AMO science.

The most recent phase of our research results from our improved understanding of fermionic systems, combined with the development in other groups of coherent molecule formation via photoassociation or the use of Feshbach resonances. We have started to analyze how the combination of these developments can be applied to the realization and manipulation of molecular fields of tailored quantum statistics, in particular in devices reminiscent of micromasers in quantum optics. Of particular interest in the context of molecule optics is the recent demonstration of Feshbach resonances between different kinds of atoms, with the potential to create large samples of polar, heteronuclear molecules. One considerable advantage of these molecules is that they can easily be accelerated by relatively modest electric field gradients, in a fashion reminiscent of the acceleration of electrons in undulators and free electron lasers. In particular, this means that these molecules should relatively easily be trapped and manipulated in centimeter-size storage rings, leading to fascinating new possibilities for atom and molecule optics.

In summary, our research in the last three years has resulted to a number of exciting results and developments. One of its most important outcomes has been to demonstrate that matter-wave optics is rapidly maturing from linear atom optics to bosonic and fermionic nonlinear and quantum atom optics, and now to molecule optics and becoming increasingly more sophisticated and promising. There is every reason to believe that the developments in the physics of ultracold atoms witnessed by our community in the last few years open up the way to exciting new developments and a wealth of potential applications in a number of areas of basic and applied physics and of engineering.

I conclude by remarking that this work would clearly not have been possible without additional sources of funding that provided considerable leverage to this ARO grant. They include participation in the ARO MURI “Strategic applications of ultracold atoms,” as well as additional grants from ONR, NSF and NASA.

6-1. Listing of Publications (Pierre Meystre, PI)

(a) Refereed papers

1. H. Pu and P. Meystre, “Creating macroscopic atomic EPR states from Bose condensates”, *Phys. Rev. Lett.* **85**, 3987 (2000).
2. S. Pötting, E. S. Lee, W. Schmitt, I. Rumyantsev, B. Mohring, and P. Meystre, “Quantum coherence and interaction-free measurements”, *Phys. Rev. A* **62**, 060101 (R) (2000).
3. M. G. Moore and P. Meystre, "Parametric amplification of coupled atomic and optical fields", in "Directions in Quantum Optics", a volume in the Memory of D. F. Walls, edited by H. J. Carmichael, R. J. Glauber and M. O. Scully, Springer Verlag, Berlin, p. 116 (2001).
4. J. Heurich, H. Pu, M. G. Moore, and P. Meystre, “Instabilities and self-oscillations in atomic four-wave mixing,” *Phys. Rev. A* **63**, 033605 (2001).
5. M. G. Moore and P. Meystre, “Atomic four-wave mixing: fermions vs. bosons”, *Phys. Rev. Lett.* **86**, 4199 (2001).
6. J. Zapata, A. M. Guzman, M. G. Moore, and P. Meystre, “Gravity-induced Wannier-Stark ladder in an optical lattice”, *Phys. Rev. A* **63**, 023607 (2001).
7. P. Meystre, “Nonlinear optics of de Broglie waves”, in “Advances in Atomic, Molecular and Optical Physics”, Vol. 47, edited by B. Bederson and H. Walther, Academic Press, San Diego, p. 1, (2001).
8. S. Raghavan, H. Pu, P. Meystre, and N. P. Bigelow, “Generation of arbitrary Dicke states in spinor Bose-Einstein condensates”, *Optics Commun.* **188**, 149 (2001).
9. S. Pötting, M. Cramer, C. H. Schwalb, H. Pu, and P. Meystre, “Coherent acceleration of Bose-Einstein condensates”, *Phys. Rev. A* **64**, 023604 (2001).
10. S. Pötting, M. Cramer, and P. Meystre, Momentum state engineering and control in Bose-Einstein condensates, *Phys. Rev. A* **64**, 063613 (2001).
11. H. Pu, W. Zhang, and P. Meystre, “Ferromagnetism in a lattice of Bose condensates”, *Phys. Rev. Lett.* **87**, 140405 (2001).
12. H. Pu, W. Zhang, M. Wilkens, and P. Meystre, “Phonon spectrum and dynamical stability of a Bose-Fermi mixture”, *Phys. Rev. Lett.* **88**, 070408 (2002).
13. P. Meystre, “Nonlinear atom optics: Recent results and prospects”, *Laser Physics* **12**, 1 (2002).
14. W. Zhang, H. Pu, C. Search, and P. Meystre, “Spin waves in a Bose-condensed atomic spin chain”, *Phys. Rev. Lett.* **88**, 060401 (2002).
15. C. P. Search, H. Pu, W. Zhang, and P. Meystre, “Diffraction of a superfluid Fermi gas by an atomic grating”, *Phys. Rev. Lett.* **88**, 110401 (2002).

16. H. Pu, C. Search, W. Zhang and P. Meystre, “Atom optics --- From de Broglie waves to Heisenberg ferromagnets”, *Fortschritte der Physik* **50**, 664 (2002).
17. C. P. Search, H. Pu, W. Zhang, B. P. Anderson and P. Meystre, “Manipulating the critical temperature for the superfluid phase transition in trapped atomic Fermi gases”, *Phys. Rev. A* **65**, 063616 (2002).
18. C. P. Search, H. Pu, W. Zhang, and P. Meystre, “Quasiparticle spectrum and dynamical stability of an atomic Bose-Einstein condensate coupled to a degenerate Fermi gas”, *Phys. Rev. A* **65**, 063615 (2002).
19. S. Pötting, M. Cramer, W. Zhang, and P. Meystre, “Raman coupler for a trapped two-component quantum-degenerate Fermi gas,” *Phys. Rev. A* **65**, 063620 (2002).
20. H. Pu, W. Zhang and P. Meystre, “Macroscopic spin tunneling and quantum critical behavior of a condensate in a double-well potential,” *Phys. Rev. Lett.* **89**, 090401 (2002).
21. K. Gross, C. P. Search, H. Pu, W. Zhang, and P. Meystre, “Magnetism in a lattice of spinor Bose condensates,” *Phys. Rev. A* **66**, 033603 (2002).
22. B. P. Anderson and P. Meystre, “Nonlinear atom optics”, *Optics and Photonics News*, June 2002, p. 20.
23. C. P. Search, S. Pötting, W. Zhang, and P. Meystre, “Input-output theory for fermions in an atom cavity”, *Phys. Rev. A* **66**, 043616 (2002).
24. W. Zhang, H. Pu, C. P. Search, P. Meystre, and E. M. Wright, "Two-fermion bound state in a Bose-Einstein condensate", *Phys. Rev. A (Rapid Communications)* **67**, 021601(R) (2003).
25. S. Pötting, P. Meystre, and E. M. Wright, "Atomic solitons in optical lattices", in “Nonlinear Photonic Crystals”, edited by R. L. Slusher and B. Eggleton, Springer Verlag (2003).
26. W. Zhang, C. P. Search, H. Pu, P. Meystre, and E. M. Wright, “Feshbach resonance-induced atomic filamentation and quantum pair correlation in atom laser beam propagation,” *Phys. Rev. Lett.* **90**, 140401 (2003).
27. C. P. Search and P. Meystre, “Noise limits on matter-wave interferometry using degenerate quantum gases,” *Phys. Rev. A (Rapid Communications)* **67**, 061601(R) (2003).
28. H. Pu, L. O. Baksmaty, W. Zhang, N. P. Bigelow, and P. Meystre, “Effective mass analysis of Bose-Einstein condensates in optical lattices — Stabilization and levitation,” *Phys. Rev. A* **67**, 043605 (2003).
29. sH. Christ, C. P. Search, and P. Meystre, “Dynamics of Fermionic Four-Wave Mixing,” *Phys. Rev. A* **67**, 063611 (2003).
30. T. Miyakawa, H. Christ, C. P. Search, and P. Meystre, "Four-wave mixing in degenerate Fermi gases: Beyond the undepleted pump approximation," *Phys. Rev. A* **67**, 063603 (2003).

31. Weiping Zhang, Ewan M. Wright, Han Pu, and Pierre Meystre, "A fundamental limit for integrated atom optics with Bose-Einstein condensates," *Phys. Rev. A* **68**, 023605 (2003).
32. Chris P. Search and P. Meystre, "Phase conjugation of a quantum-degenerate atomic Fermi beam," *Phys. Rev. Lett.* **91**, 100401 (2003).
33. Han Pu, Weiping Zhang, and Pierre Meystre, "Wave mixing of optical pulses and Bose-Einstein condensates," *Phys. Rev. Lett.* **91**, 150407 (2003).
34. Chris P. Search, Weiping Zhang, and P. Meystre, "A molecular micromaser," *Phys. Rev. Lett* **91**, 190401 (2003).
35. B. P. Anderson and P. Meystre, "Nonlinear atom optics," *Contemporary Physics* **44**, 473 (2003).
36. C. P. Search, W. Zhang, and P. Meystre, "Inhibiting three-body recombination in atomic Bose-Einstein condensates," *Phys. Rev. Lett.* **92**, 140401 (2004).
37. C. P. Search, T. Miyakawa, and P. Meystre, "A lattice array of molecular micromasers," *Optics Express* **12**, 30 (2004).
38. C. P. Search and P. Meystre, "Molecular matter-wave amplifier," *Phys. Rev. Lett.* **93**, 140405 (2004).

(b) Papers published in proceedings

1. H. Pu, M. G. Moore, and P. Meystre, "Atomic squeezing and entanglement from Bose-Einstein condensates", in "Modern Challenges in Quantum Optics", edited by M. Orszag and J. C. Retamal, Springer Verlag (Berlin), p. 161 (2001).
2. C. P. Search, H. Pu, W. Zhang, and P. Meystre, "Magnetism of Bose-Einstein condensates on optical lattices," to be published in "Condensed Matter Theories XXVI", edited by J. da Providencia and J. W. Clark, Nova Science Publishers.

(c) Manuscripts presented at meetings but not published

1. P. Meystre, "Quantum coherence in quantum and atom optics, invited talk, QUEST2000, Workshop, Santa Fe (NM) 2000.
2. P. Meystre, "Recent advances in nonlinear atom optics", invited talk, TAMU/ONR Workshop on Quantum Optics, Jackson Hole Resort (WY), 2000.
3. M. G. Moore and P. Meystre, "Atomic four-wave mixing: fermions vs. bosons", invited talk, TAMU/ONR Workshop on Quantum Optics, Jackson Hole Resort (WY) 2000.}.
4. S. Pötting and P. Meystre, "Quantum coherence and interaction-free measurements", invited talk, TAMU/ONR Workshop on Quantum Optics, Jackson Hole Resort (WY) 2000.
5. P. Meystre, "Nonlinear wave mixing and matter-wave amplification", invited talk, Quantum Optics I, Santiago, Chile, 2000.

6. P. Meystre, "Marginally acceptable personal, anecdotal and technical remarks on Joe Eberly, cavity QED, and atom optics", invited talk, Quantum Control of Atoms and Fields, a Symposium in Honor of J. H. Eberly, Rochester (NY), 2000.
7. P. Meystre, "Nonlinear atom optics: bosons vs. fermions", invited talk, 8th Rochester Conference on Coherence and Quantum Optics, Rochester (NY), 2001.
8. P. Meystre, "Nonlinear atom optics: Recent results and prospects", Plenary talk, International Laser Physics Conference LPHYS'01, Moscow, Russia, 2001.
9. P. Meystre, "Nonlinear atom optics of bosons and fermions", invited talk, Gordon Research Conference on Nonlinear Optics, New London (NH), 2001.
10. P. Meystre, "Nonlinear atom optics --- From de Broglie to Heisenberg", invited talk, Alexander von Humboldt 18th Symposium, "100 Years Werner Heisenberg --- Works and Impact", Bamberg, Germany, 2001.
11. P. Meystre "Nonlinear atom optics", invited talk, Symposium in the Honor of Professors Chatelain and Quattropani", Swiss Federal Institute of Technology, Lausanne, Switzerland, 2001.
12. M. Cramer, C. Schwalb, S. Poetting, H. Pu and P. Meystre, "Coherent acceleration of Bose-Einstein condensates", contributed talk, 2nd Pan-Pacific Basin Workshop on Microgravity Sciences, Pasadena (CA), 2001.
13. Sierk Poetting, Marcus Cramer, Christian H. Schwalb, Han Pu, and Pierre Meystre, "Lossless acceleration of Bose-Einstein condensates", contributed paper, DAMOP Annual Meeting, London, Ontario, 2001.
14. H. Pu, W. Zhang and P. Meystre, "Phonon excitations and stability of a Bose-Fermi mixture quantum gas", contributed paper, 8th Rochester Conference on Coherence and Quantum Optics, Rochester, (NY) 2001.
15. P. Meystre, "Nonlinear atom optics", Plenary Talk, German Physical Society, Divisions of Atomic, Molecular and Optical Physics Annual Meeting, Osnabrück, Germany, 2002.
16. P. Meystre, "Nonlinear optics with matter waves", Joint invited tutorial, International Quantum Electronics Conference and Conference on Lasers, Applications, and Technologies, Moscow, Russia, 2002.
17. P. Meystre, "Nonlinear atom optics of bosons and fermions", invited talk, International Nonlinear Optics Conference, NLO2002, Maui (HW) 2002.
18. P. Meystre, "Magnetism on lattices of Bose-Einstein Condensates", invited talk, XXIV International Workshop on Condensed Matter Theories, Luso, Portugal, 2002.
19. K. Gross, C. P. Search, H. Pu, W. Zhang, and P. Meystre, "Magnetism in a lattice of spinor Bose condensates", contributed paper, 2002 NASA/JPL Workshop on Fundamental Physics in Space, Dana Point, California, 2002.

20. H. Pu, W. Zhang, M. Wilkens, and P. Meystre, “Dynamical instability of a dilute quantum degenerate Bose-Fermi mixture”, contributed paper, American Physical Society, DAMOP Annual Meeting, Williamsburg (VA) 2002.
21. W. Zhang, H. Pu, C. P. Search, and P. Meystre, “Spin dynamics of Bose-Einstein condensates in optical lattices”, American Physical Society, DAMOP Annual Meeting, Williamsburg (VA) 2002.
22. S. Pötting, M. Cramer, W. Zhang, and P. Meystre, “Atomic coupler for a trapped quantum degenerate Fermi gas”, contributed paper, American Physical Society, DAMOP Annual Meeting, Williamsburg (VA) 2002.
23. P. Meystre, “Atom optics,” Lecture Series (10 hours), Troisième Cycle Romand de Physique, Swiss Federal Institute of Technology, Lausanne, Switzerland, 2003.
24. P. Meystre, “Fermionic atom optics --- a tutorial”, invited talk, TAMU-ONR-DARPA Workshop on Quantum Optics, Grand Targhee (WY) 2003
25. P. Meystre, “Cavity de Broglie optics – a molecular micromaser,” invited talk, QUEST 2003 Symposium, Santa Fe, (NM) 2003.
26. P. Meystre, “Four-wave mixing of fermionic matter waves” invited talk, 12th International Laser Physics Workshop LPHYS'03, Hamburg, Germany, 2003.
27. P. Meystre, “Nonlinear mixing of pulsed optical and matter waves,” invited talk, 12th International Laser Physics Workshop LPHYS'03, Hamburg, Germany, 2003.
28. P. Meystre, “Cavity de Broglie optics – The molecular micromaser,” invited talk, 2003 US-Japan Joint Seminar ‘Quantum Correlations and Coherence’, Yatsugatake, Japan, 2003.
29. Weiping Zhang, C. P. Search, Han Pu, P. Meystre, and E. M. Wright , “Quantum pair correlation in the Feshbach-resonance-induced atomic filamentation of a propagating atom-laser beam,” contributed paper, APS Division of Atomic, Molecular and Optical Physics Annual Meeting, Boulder (CO), 2003.
30. C. P. Search and P. Meystre , “Noise limits in matter-wave interferometry using degenerate quantum gases,” contributed paper, APS Division of Atomic, Molecular and Optical Physics Annual Meeting, Boulder (CO), 2003.
31. Han Pu, L. Baksmaty, Weiping Zhang, N. Bigelow, and P. Meystre, “Dynamics of Bose-Einstein condensates in optical lattices: an effective mass approach,” contributed paper, APS Division of Atomic, Molecular and Optical Physics Annual Meeting, Boulder (CO), 2003.
32. P. Meystre, “Nonlinear matter-wave optics of atoms and molecules,” invited talk, Binational Consortium of Optics Winter School, Tucson (AZ) 2004.
33. P. Meystre, “Fermionic atom optics,” invited talk, NASA/JPL Workshop on Physics for Planetary Exploration, Solvang (CA) 2004.

34. P. Meystre, "Fermionic atom optics," invited talk, 2004 Cold Gases Program, Kavli Institute for Theoretical Physics, Santa Barbara (CA) 2004.
35. P. Meystre, "Micromaser-like generation of molecular fields," invited talk,
36. M. Jääskeläinen, Weiping Zhang, and P. Meystre, "Phase resolution in matter-wave interferometry," contributed paper, DAMOP-DAMP Annual Meeting, Tucson (AZ) 2004.
37. D. Meiser, C. P. Search, and P. Meystre, "Diffraction of ultra-cold fermions off of quantized fields: Standing waves versus traveling waves," contributed paper, DAMOP-DAMP Annual Meeting, Tucson, (AZ) 2004.
38. T. Miyakawa, C. P. Search, and P. Meystre, "Phase coherence in molecular micromasers with interwell tunneling," contributed paper, DAMOP-DAMP Annual Meeting, Tucson (AZ) 2004.
39. C. P. Search, Weiping Zhang, and P. Meystre, "Inhibiting three-body recombination in atomic Bose-Einstein condensates," contributed paper, DAMOP-DAMP Annual Meeting, Tucson (AZ) 2004.
40. D. Meiser and P. Meystre, "Using molecules to study correlation functions of ultracold atomic gases," contributed paper, Fall Meeting of the American Physical Society Four-Corners Section, Albuquerque (NM) 2004.

(d) Papers submitted but not published

1. D. Meiser, C. P. Search, and P. Meystre, "Diffraction of ultra-cold fermions by a quantized light fields: Standing versus traveling waves," to be published in Phys. Rev. A.
2. T. Miyakawa, C. P. Search, and P. Meystre, "Phase coherence in a driven double-well system," to be published in Phys. Rev. A.
3. M. Jääskeläinen, W. Zhang, and P. Meystre, "Limits to phase resolution in matter-wave interferometry," to be published in Phys. Rev. A.
4. C. P. Search and P. Meystre, "Nonlinear and quantum optics of atomic and molecular fields," to be published in Progress in Optics.

5-2. Summary of Results, Experimental Component (Poul S. Jessen, Co-PI)

Our experimental research has focused on the preparation and measurement of Cs atomic ensembles in non-classical states, such as spin squeezed states and other types of entangled/correlated manybody states that hold promise for improved atomic clocks and atom interferometer based sensors. To this end we have pursued two radically different approaches to quantum manybody control. One effort has worked towards the use of atoms trapped in optical lattices as qubits, with the goal of implementing single- and two-qubit quantum gates in this system. Once successful, these basic elements can be assembled in a quantum circuit that can produce highly entangled manybody states. This problem is closely related to (but simpler than) quantum computation, and our work in this area has been heavily leveraged by two separate grants to develop the basic elements of a neutral atom quantum processor. A second effort has focused on the use of probe polarization spectroscopy to implement non-perturbing, continuous weak measurements on atomic ensembles. When such a measurement is sensitive enough to resolve the quantum fluctuations associated with a collective observable, backaction will be induced on the collective manybody state and the uncertainty of the measured value can be squeezed.

During the grant period we have made significant progress towards the realization of atomic qubits and quantum gates in optical lattices. We have demonstrated the ability to efficiently load atoms into very deep optical lattices, and carefully characterized the properties of the trapped atom/lattice system. To serve as qubits the trapped atoms must be initialized in a specific magnetic sublevel in the ground hyperfine manifold, and in the vibrational ground state of their individual wavelength-sized microtraps. We have sought to accomplish this via simultaneous Raman sideband cooling in three dimensions. In doing so we have found that it is relatively straightforward to achieve substantial cooling, but quite challenging to fine-tune performance to achieve near unit population of the target state. Our best efforts have been able to prepare in excess of 97% of the atoms in the $|F = 3, m_F = 3\rangle$ state, and ~98% in the ground state of motion along the (vertical) z -axis. In principle our cooling scheme should produce very similar levels of vibrational excitation along the (horizontal) x - and y -axes. This would imply an overall population of ~93% in the target state, though we cannot rule out that the vibrational temperatures might be higher in the x - y plane. Further fine tuning will require better means to simultaneously measure the vibrational excitation in three dimensions. In the meantime, the quality of our qubit initialization is probably sufficient for initial explorations of single- and two-qubit quantum control.

Following initialization, we have worked to demonstrate coherent manipulation of our atomic qubits on the Bloch sphere. Because we are working with a large ensemble of atomic trapped in an optical lattice this requires that inhomogeneities across the ensemble be controlled and ultimately circumvented through the use of refocusing and spin-echo techniques. The most important sources of inhomogeneity in our system are magnetic fields and the lattice trapping potential, both of which may vary in both space and time. To isolate and address the more serious problem of lattice inhomogeneity we have worked mostly with qubits encoded in the $F = 3, 4$, $m_F = 0$ clock doublet, which is highly insensitive to magnetic fields. To further simplify the problem, at least initially, we have used a vertically oriented 1D lattice rather than a full 3D lattice, which reduces the number of potentially inhomogeneous lattice beams from six to two. We have successfully driven Rabi oscillations with an initial contrast of at least 90%, and also observed Ramsey Fringes in both the frequency and time domain. We have also explored the qubit dynamics resulting from spin-echo sequences of microwave pulses, thereby eliminating dephasing from ensemble inhomogeneities and demonstrating negligible decoherence on a ~ 2

ms timescale. This shows that neither decoherence nor dephasing from ensemble inhomogeneities will pose serious limitations for experiments on two-qubit controlled collisions, which will typically take place on a ms timescale. We have concluded that further optimization of single-qubit control requires better – in particular real-time – diagnostic methods, and have worked extensively on optical probes of ground state spins and pseudospins/qubits (see below). With improved ways of observing the qubit dynamics we hope to wrap up our efforts on qubit initialization and control, and proceed towards the demonstration of two-qubit quantum gates based on controlled collisions.

In our second research effort we have made major progress towards the implementation of real-time, non-perturbing optical probes of atomic spins and pseudospins, with the ultimate goal of exploring quantum feedback and the deterministic generation of spin squeezing and massive entanglement. To this end we have developed a very detailed understanding of the interaction between a far-off-resonance laser field and alkali atoms in the electronic ground state. The best known example of optical probing is the use of Faraday rotation of a far-off-resonance probe beam to measure a component of the spin-angular momentum in a specific hyperfine ground state. We have performed a very careful evaluation of our Faraday measurement setup in the context of Larmor precession, looking in particular at the signal-to-noise ratios (SNRs) in measurements of the collective spin and the signal dephasing times that can be achieved for a wide range of probe intensity and detuning. Along with this effort we developed a detailed quantitative model of Faraday rotation measurements, and found generally excellent agreement between the measured and predicted SNRs. Perhaps the most important insight from this work is the tradeoff between sensitivity and disturbance. Our model and data shows that the SNR of a spin measurement scales as $OD \times \sqrt{\tau_m / \tau_s}$, where OD is the optical depth on resonance and τ_m the response time of the measurement apparatus (meter), and where the dependence on probe field parameters is entirely given by $\tau_s = \gamma_s^{-1}$, the mean time between photon scattering events. To produce the maximum amount of quantum back-action it is essential that the measurement output be integrated over the longest possible measurement window. We have found that spin dynamics in the presence of the Faraday probe is dominated by a nonlinear term generated by the atom-probe coupling, which leads to rapid collapse and revival of the mean spin during Larmor precession. The nonlinear collapse is generally much faster than the decay of the collective spin due to optical pumping, and therefore plays the main role in determining the QND window of the measurement. Furthermore, both the nonlinearity and measurement strength are proportional to the rate of probe photon scattering, making the integrated back-action independent of probe intensity and detuning. We have shown that it can be effectively cancelled by applying a bias magnetic field at a specific angle with the probe polarization, and that the non-perturbing nature of the measurement can be recovered on the much longer timescale set by probe photon scattering.

Our work on Faraday probing of spin-angular momenta called attention to the importance of the oft-overlooked rank-2 tensor component of the AC Stark- or light shift. Based on this tensor coupling we have developed a new, related technique that looks for induced ellipticity due to birefringence of the atomic sample, rather than polarization rotation via the Faraday effect. Towards the end of the grant period we were able to demonstrate a real-time, non-perturbing measurement of the z -component of the pseudo-spin associated with the clock doublet in ^{133}Cs , whose performance was in good agreement with the predictions of a full master equation simulation of the atomic dynamics. At the time of writing, we have shown that this basic approach also permits real-time, non-perturbing measurements of other pseudospins (qubits) embedded in the ground hyperfine manifold. A further intriguing aspects of the full tensor light shift is that it allows the implementation of arbitrary unitary transformations of the spin-angular

momentum. We are continuing to explore the possibilities for quantum measurement and control in this system, including spin squeezing on the atomic clock transition, real-time density matrix reconstruction, and the study of nonlinear dynamics and quantum chaos.

6-2. Listing of Publications (Poul S. Jessen, Co-PI)

(a) Refereed papers

1. G. A. Smith, S. Chaudhury, P. S. Jessen, A. Silberfarb and I. H. Deutsch, *Continuous weak measurement and nonlinear dynamics in a cold spin ensemble*, Phys. Rev. Lett. 93, 163602 (2004)
2. P. S. Jessen, I. H. Deutsch and R. Stock, *Quantum Information Processing with Trapped Neutral Atoms*, Quant. Inf. Proc. 3, 15 (2004).
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1. H. Deutsch and P. S. Jessen, *Quantum Information Processing in Optical Lattices: Cold Atomic Qubits in a Virtual Crystal of Light*, IEEE LEOS Newsletter **16**, No 2, 3 (2002).

(c) Manuscripts presented at meetings but not published

1. P. S. Jessen, *Continuous Optical Measurement and Control of Atomic Spin Ensembles*, PRACQSYS'04, California Institute of Technology, Pasadena, California, 21-24 August 2004. (Invited)
2. P. S. Jessen, *Optical Measurement and Control of Atomic Spin Ensembles*, QUEST 2004 Summer Workshop, Santa Fe, New Mexico, 9-13 August 2004. (Invited)
3. P. S. Jessen, *Quantum Computing with Trapped Neutral Atoms*, Computing Beyond Silicon Summer School, California Institute of Technology, Pasadena, California, 7 July 2004. (Invited)
4. P. S. Jessen, *Elements of QIP with Trapped Neutrals at the University of Arizona*, NIST Workshop on Quantum Information with Optically Controlled Neutral-Atom Qubits, Gaithersburg, Maryland, 10-11 June 2004.
5. G. A. Smith, S. Chaudhury and P. S. Jessen, *Faraday Measurements and Nonlinear Spin Dynamics in Laser Cooled Atomic Ensembles*, 2004 meeting of the Division of Atomic and Molecular Physics, Tucson, Arizona, May 25-29, 2004.
6. W. Rakreungdet, K. F. Lee and P. S. Jessen, *Quantum Control of Atomic Qubits in a 3D Optical Lattice*, 2004 meeting of the Division of Atomic and Molecular Physics, Tucson, Arizona, May 25-29, 2004.
7. P. S. Jessen, *Faraday Spectroscopy: A Quantum Probe for Ultracold Spin Ensembles*, Sixth Annual Workshop of the SQuInT Network, San Diego, California, 20-22 February 2004. (Invited)
8. S. Chaudhury, G. Smith and P. S. Jessen, *Faraday Measurements and Nonlinear Dynamics of Atomic Spin Ensembles*, Sixth Annual SQuInT Workshop, San Diego, California, February 20-22, 2004. (Poster)
9. W. Rakreungdet, K. F. Lee and P. S. Jessen, *Initializing and Manipulating Atomic Qubits in a 3D Optical Lattice*, Fifth Annual SQuInT Workshop, San Diego, California, February 20-22, 2004. (Poster)
10. S. Chaudhury, G. Smith and P. S. Jessen, *Continuous Measurement of Atomic Spin in an Optical Lattice*, Laser Science XIX, FiO/LS (OSA), Tucson, Arizona, October 7th, 2003.
11. P. S. Jessen, *Faraday spectroscopy: a continuous probe of linear and nonlinear spin dynamics*, QUEST 2003 Summer Workshop, Santa Fe, New Mexico, 11-15 August 2003. (Invited)
12. P. S. Jessen, *Faraday spectroscopy in an optical lattice: a continuous probe of atom dynamics*, SPIE conference on Fluctuations and Noise in Photonics and Quantum Optics, Santa Fe, New Mexico, 2-4 June 2003. (Invited)

13. W. Rakreungdet, L. Harrison and P. S. Jessen, *Sideband Cooling and Qubit initialization in a 3D Optical Lattice*, 2003 meeting of the Division of Atomic and Molecular Physics, Boulder, Colorado, May 20-24, 2003.
14. G. Smith, S. Chaudhury and P. S. Jessen, *Continuous Measurement of the Collective Spin of Laser Cooled Atoms*, Fifth Annual SQuInT Workshop, Santa Fe, New Mexico, February 7- 9, 2003. (Poster)
15. W. Rakreungdet and P. S. Jessen, *Raman Sideband Cooling in a 3D Optical Lattice*, Fifth Annual SQuInT Workshop, Santa Fe, New Mexico, February 7- 9, 2003. (Poster)
16. P. S. Jessen, *Qubits and Quantum Gates in Optical Lattices*, Joint IPAM/MSRI Workshop on Quantum Computing, Los Angeles, California, 21-23 October 2002. (Invited)
17. G. Smith, S. Chaudhury and P. S. Jessen, *Continuous Measurement of the Mean Magnetic Moment of a Cold Atomic Vapor*, 2002 Meeting of the Division of Atomic and Molecular Physics, Williamsburg, Virginia, 29 May - 1 June 2002.
18. P. S. Jessen, *Mesoscopic Quantum Coherence in an Optical Lattice*, Annual APS March Meeting 2002, Indianapolis, Indiana, 18-22 March, 2002. (Invited)
19. P. S. Jessen, *Continuous measurement and feedback on atomic motion in optical traps*, Fourth Annual Workshop of the SQuInT Network, Boulder, Colorado, 8-10 March 2002. (Invited)
20. P. S. Jessen, *Spinor Wavepacket Dynamics in a Magneto-Optical Double-Well lattice*, OSA/ILS Annual Meeting 2001, Long Beach, California, 14-18 October 2001. (Invited)
21. P. S. Jessen, *Methods to Measure angular Momentum States, and Their Possible Application to Quantum Chaos and Control*, QUEST 2001 Summer Retreat, Santa Fe, New Mexico, 6-10 August 2001. (Invited)
22. P. S. Jessen, *Quantum Control and Quantum Logic in Optical Lattices*, P. S. Jessen, Gordon Research Conference on Atomic Physics, Williamstown, Massachusetts, June 17-21 2001. (Invited)
23. Kit-Iu Cheong and P. S. Jessen, *Raman Sideband Cooling in Optical Lattices*, Gordon Research Conference on Atomic Physics, Williamstown, Massachusetts, June 17-21 2001. (Poster)
24. P. S. Jessen, *Coherent Tunneling and Quantum Control in an Optical Double-well Potential*, P. S. Jessen, ICOLS '01, Snowbird, Utah, June 11-15 2001. (Invited)
25. P. S. Jessen, *Spinor Wavepacket Control in Optical Double-well Potentials*, P. S. Jessen, 2001 meeting of the APS Division of Atomic and Molecular Physics, London, Ontario, 16-19 May 2001. (Invited)

26. P. S. Jessen, *Quantum Control in nanoscale atom traps*, Arizona Research Forum on Nanotechnology, Tucson, Arizona, 21 March 2001. (Invited)
27. G. Klose and P. S. Jessen, *Measuring the quantum state of a large angular momentum*, Third Annual Workshop of the SQuInT Network, Pasadena, California, 2-4 March 2001. (Invited)
28. G. Klose and P. S. Jessen, *Quantum Tomography - Plato's Prisoner in the 21st Century*, Industrial Affiliates Meeting, Optical Sciences Center, Tucson, Arizona, February 27, 2001.
29. P. S. Jessen, *Quantum Control and Entanglement Engineering with Cold Trapped Atoms*, International Conference on Experimental Implementation of Quantum Computation (IQC 01), Sydney, Australia, 16-19 January 2001. (Invited)

7. List of all participating scientific personnel, including degrees earned.

Pierre Meystre (PI)
 Poul S. Jessen (Co-PI)
 Twaje Byakunda (research specialist)
 S. Chaudhury (graduate student)
 K.-I. Cheong (graduate student)
 Henning Christ (graduate student, MS degree, U. Marburg, Germany, 2003)
 Marcus Cramer (graduate student, MS degree, U. Marburg, Germany, 2003)
 Dennis Douglas (graduate student)
 Mushin Eralp (graduate student)
 L. B. Harrison (graduate student)
 G. Klose (Ph. D. Degree, U. of Arizona, 2001)
 K. F. Lee (postdoctoral fellow)
 B. E. Mischuch (graduate student)
 Cesar Brito Nevarez (graduate student)
 Sierk Poetting (PhD Degree, U. Munich, Germany 2004)
 W. Rakreungdet (graduate student)
 K. M. Schulz (graduate student)
 Chris Search (postdoctoral fellow)
 G. A Smith (graduate student)

8. Report of Inventions

None